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(71) Applicant: ABIOMED, INC. [US/US]; 22 Cherry Hill Drive, Danvers, MA 01923 (US).

(72) Inventor: ZARINETCHI, Farhad; 9 Bradford Road, Chelmsford, MA 01863 (US).

(74) Agents: CAHILL, Ronald, E. et al.; Nutter, McClennen & Fish, LLP, One International Place, Boston, MA 02110-2699 (US).

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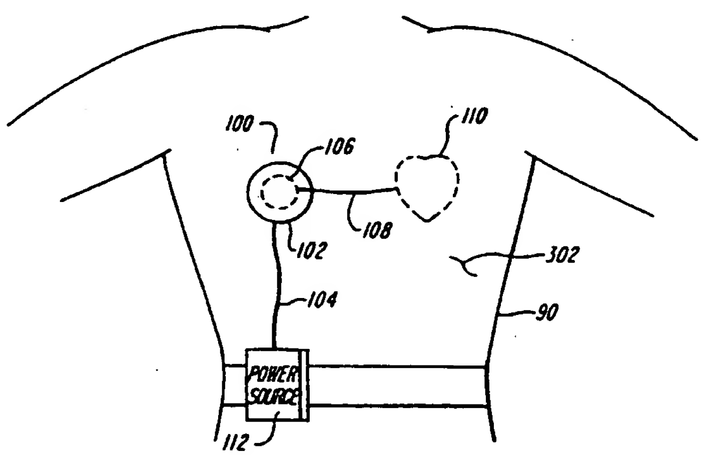

(57) Abstract: Methods and apparatus for transferring energy across a boundary, to provide power to devices (110) internal to the body, comprising: a transcutaneous energy transfer (TET) device (100) functioning as a power transformer including an "oversized" primary winding (102) affixed in proximity to an exterior surface of the skin, and a secondary winding (106) implanted in the body and aligned with the primary winding. A first area delimited by the primary winding, from which a magnetic field is generated, is larger than a second area delimited by the secondary winding of the TET transformer, which intercepts the magnetic field. The larger area of the "oversized" primary winding allows a significant displacement between the primary and secondary windings while nonetheless maintaining uniformity of the magnetic field that impinges on the secondary winding. As a result, the secondary winding is capable of providing sufficient power to one or more implanted devices notwithstanding shifts in the relative positions of the windings.

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APPARATUS FOR TRANSFERRING ENERGY ACROSS A BOUNDARY

Background of the Invention

1. Field of the Invention

The present invention relates to energy transfer methods and devices, and more particularly, to transmitting energy from a position on one side of a boundary and receiving energy at a position on another side of a boundary, wherein the energy received is not significantly affected by more than nominal changes in the relative transmitting and receiving positions.

2. Related Art

In a variety of scientific, industrial, and medically related applications, it may be desirable to transfer energy or power (energy per unit time) across some type of boundary. For example, one or more devices that require power (e.g., electrical, mechanical, optical, and acoustic devices) may be located within the confines of a closed system, or "body," in which it may be difficult and/or undesirable to also include a power source. The closed system or body may be delimited by various types of boundaries, and the system internal to the boundary may be living or inanimate, may perform a variety of functions, and may have a variety of operational and physical requirements and/or constraints. In some cases, such requirements and constraints may make the implementation of an "internal" power source for internally located devices problematic.

For example, in some systems, repeated entry into the system may be undesirable for a variety of reasons. In such a case, implementing an internal power source such as a battery, for example, may be impractical. Typically, a battery is capable of providing power only for a finite time period, after which the battery must be changed or recharged. Accordingly, entry into the system would likely be required to change or recharge the battery. In other systems, significant internal power requirements and a limited internal space may prohibit the implementation of a suitably sized internal power source. In yet other systems, contamination and/or security issues may pose particular challenges in implementing an internal power source. For any combination of the foregoing and other reasons, a power

source external to the system and some feasible means of transferring power from the external source to one or more internal devices may be preferable in some applications.

One example of a closed system is the human body. In some medically related and scientific applications, a variety of prosthetic and other devices that require power may be surgically implanted within various portions of the body. Some examples of such devices include a synthetic replacement heart, a circulatory blood pump or ventricular assist device (VAD), a cochlear (ear) implant, a pacemaker, and the like. With respect to the human body, issues such as repeated reentry or surgery, internal space limitations, and contamination may make the implementation of an internal power source for the implanted device impractical. In particular, implanting a suitably sized internal power source (such as a battery) that would likely require periodic maintenance may pose undesirable additional health risks for the patient and present additional challenges to a surgeon.

Accordingly, in some medical implant applications, "transcutaneous energy transfer" (TET) devices are employed to transfer energy from outside the body to inside the body, to provide power to one or more implanted prostheses or devices from an external power source. One example of a conventional TET device is a transformer that includes a primary winding (or coil) external to the body and a secondary winding internal to the body. Both the primary and secondary windings generally have essentially planar (flat) geometries, typically are circular in shape, and are placed proximate to respective outer and inner layers of a patient's skin; hence, the term "transcutaneous" commonly refers to energy transfer "through the skin." Energy is transferred from the primary winding to the secondary winding in the form of a magnetic field. The implanted secondary winding converts the transferred energy in the magnetic field to electrical power for the implanted device, which acts as a "load" on the secondary winding.

In general, TET devices differ from conventional power transformers in that power transformers typically include a magnetic core around which the primary and secondary windings are wound. The magnetic core provides a "low resistance" path (a low reluctance magnetic circuit) for the magnetic field to travel between the primary and secondary windings. Generally, the energy (or power) transfer efficiency of a transformer is related to the reluctance of the magnetic circuit through which the magnetic field travels. The reluctance of the magnetic circuit in turn is a function of the material through which the magnetic field passes from the primary to the secondary windings (e.g., a magnetic core) and the relative arrangement and spatial positioning of the windings relative to each other.

Typically, a low reluctance magnetic circuit including a magnetic core that structurally couples the primary and secondary windings, as in a conventional power transformer, provides for a high energy transfer efficiency.

One potential problem associated with transferring energy across a boundary (e.g., into a closed system or body) is that structurally coupling the primary and secondary windings (e.g., via a magnetic core) may be difficult or impossible. For example, in the case of the conventional TET device described above, the nature of the application in the human body (i.e., the respective external and internal locations of the transformer windings) essentially precludes using a magnetic core to structurally couple the windings. Hence, the magnetic field generated by the primary winding must travel to the secondary winding through the skin and perhaps other body tissues, which typically are less magnetically "permeable" than a magnetic core. Hence, the windings separated by skin and/or other body tissue form a higher reluctance magnetic circuit and, as a result, conventional TET devices generally have a relatively lower energy transfer efficiency.

In view of the foregoing, one focus of conventional TET device designs primarily has been on maintaining an optimum magnetic coupling between the primary and secondary windings, based on the physical arrangement and spatial positioning of the windings relative to each other. A measure of magnetic coupling between the windings typically is expressed as a mutual inductance or a coupling coefficient. In general, magnetic coupling between the windings increases as the windings are spatially aligned such that the secondary winding intercepts a larger portion of the magnetic field generated by the primary winding. Additionally, magnetic coupling between the windings generally increases as the distance separating the windings decreases. Thus, to optimize magnetic coupling, conventional TET device designs generally have involved similarly-sized mutually-aligned windings separated by a small distance.

In some applications, the size of transformer windings practically may be constrained by limitations imposed by the system in which they are implemented. In particular, with respect to conventional TET devices used in connection with the human body, the size of the windings in such devices (specifically the internal secondary winding) generally is constrained by various physical limitations of the human body. As a result, attempts at optimizing magnetic coupling in conventional TET device designs generally are limited to selecting the largest practical size for the secondary winding, and then selecting an identical size for the primary winding. As a result, practical winding sizes of conventional TET

devices for human applications typically have been limited to less than approximately three inches (75 mm) in diameter.

Due to size limitations imposed by the human body, another focus of conventional TET device designs has been on designing the smallest possible windings to provide sufficient power to an implanted device. Such a design criterion typically requires, however, that the distance between the primary and secondary windings be constrained to be as small as possible, to insure an optimum magnetic coupling between the windings. For example, an "effective operating range" (i.e., the axial distance through the skin that separates the primary and secondary windings) of conventional TET devices generally is limited to less than .5 inches (5-10 mm).

One problem with conventional TET devices as a result of such a limited operating range generally is that the energy transferred to the secondary winding, and hence the power supplied by the secondary winding to the implanted device, is quite sensitive to more than nominal or trivial physical displacements of either the primary winding or the secondary winding from an "optimum" position. In some conventional TET devices, the power supplied by the secondary winding is sensitive to any physical displacement of either the primary or secondary winding from an optimum position. More specifically, a small displacement of one winding relative to the other can result in a substantial variation (and in a worse case scenario, a substantial decrease) in the magnetic coupling, and hence the energy transfer efficiency, of the TET device. As a result of such variations, the power ultimately supplied by the secondary winding to implanted prostheses or other devices may vary unpredictably with winding displacement.

Implanted prostheses or other devices, and particularly an implanted device that performs a life-sustaining function, generally must have a consistent source of available power. Without a consistent power source, the implanted device may function erratically or intermittently. Such erratic or intermittent operation can have undesirable and, in some cases, serious life-threatening effects on the patient.

Accordingly, as discussed above, the need for consistent power practically constrains both the axial distance that separates the primary and secondary windings as well as the alignment of the windings in a conventional TET device during normal "use." Such constraints present a disadvantage to the patient, whose mobility may be substantially limited so as to prevent shifting and misalignment between the windings. Additionally, such constraints may preclude the use of ointments or bandages in connection with the TET

device, which may add to the axial displacement between the windings, and may also preclude the use of the TET device through clothing, which may exacerbate both lateral and axial shifting between the windings with patient movement.

Summary of the Invention

According to one embodiment, an apparatus of the invention comprises a first energy transfer element to transmit energy and a second energy transfer element to receive at least a portion of the energy. The first energy transfer element delimits a first area through which the energy is transmitted, and the second energy transfer element delimits a second area through which at least a portion of the energy is received as received energy. The first area delimited by the first energy transfer element is at least twice as large as the second area delimited by the second energy transfer element.

According to another embodiment, an apparatus of the invention comprises a first energy transfer element to transmit energy, the first energy transfer element located at a first position on a first side of a boundary, and a second energy transfer element located at a second position on a second side of a boundary to receive at least a portion of the energy transmitted by the first energy transfer element as received energy. The first and second energy transfer elements are constructed and arranged such that the received energy is not significantly affected by a more than nominal change in at least one of the first position and the second position.

According to another embodiment, a method of the invention for transferring energy comprises acts of a) transmitting the energy from a first area having a first position on a first side of a boundary, and b) receiving at least a portion of the energy as received energy in a second area having a second position on a second side of the boundary. The first and second areas are respectively dimensioned and aligned such that the received energy is not significantly affected by a more than nominal change in at least one of the first and second positions.

According to another embodiment, a transcutaneous power transformer of the invention comprises a primary winding located external to a body to generate a first magnetic flux, and a secondary winding located internal to the body and positioned relative to the primary winding so as to receive at least a portion of the first magnetic flux as a second magnetic flux. The primary winding and the secondary winding are constructed and arranged such that the secondary winding is capable of providing a load with a sufficient power based

upon the second magnetic flux, irrespective of a significant spatial displacement of at least one of the primary winding and the secondary winding.

According to another embodiment, a transcutaneous energy transfer apparatus of the invention comprises a primary coil located external to a body to transmit a magnetic field and a secondary coil located internal to the body to receive at least a portion of the magnetic field. The primary coil and the secondary coil are constructed and arranged such that a magnetic coupling between the primary coil and the secondary coil is significantly insensitive to a more than nominal spatial displacement of at least one of the primary coil and the secondary coil.

According to another embodiment, a primary winding of the invention for use in a transcutaneous energy device, the transcutaneous energy device comprising the primary winding and a secondary winding, comprises at least one winding turn to transmit energy based on an electrical signal applied to the winding turn. The primary winding delimits a first area through which the energy is transmitted, wherein the first area is at least twice as large as a second area delimited by the secondary winding.

According to another embodiment, a primary winding of the invention for use in a transcutaneous energy device, the transcutaneous energy device comprising the primary winding and a secondary winding, comprises at least one winding turn to transmit energy based on an electrical signal applied to the winding turn. The primary winding delimits a first area through which the energy is transmitted, wherein the first area is at least approximately 9.7 square inches.

Brief Description of the Drawings

The accompanying drawings are not intended to be drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every drawing.

In the drawings:

Fig. 1 is a diagram showing an example of an implementation of an energy transfer device in a human body, according to one embodiment of the invention;

Fig. 2 is a diagram showing a more detailed side view of the energy transfer device shown in Fig. 1, according to one embodiment of the invention;

Fig. 3 is a diagram showing a more detailed top view of the energy transfer device shown in Fig. 1, according to one embodiment of the invention;

Fig. 4 is a diagram similar to Fig. 3, showing a top view of an energy transfer device according to another embodiment of the invention;

Fig. 5 is a diagram showing a three-dimensional view of a winding used in an energy transfer device according to one embodiment of the invention, and the effect of winding geometry on magnetic field;

Fig. 6 is a diagram showing a two-dimensional view of the winding of Fig. 5, and the magnetic field in greater detail;

Fig. 7 is a graph comparing the relative magnetic field strength at various normal or axial distances from a winding for two differently sized windings similar to that shown in Fig. 5;

Fig. 8 is a graph similar to Fig. 7 comparing the relative magnetic field strength at various lateral distances from an axis of a winding for two differently sized windings;

Fig. 9 is a diagram showing a three-dimensional view of the energy transfer device of Figs. 1, 2, and 3, according to one embodiment of the invention;

Fig. 10 is a diagram showing the energy transfer device of Fig. 9, with a secondary winding of the device laterally displaced; and

Fig. 11 is a diagram showing a more detailed two-dimensional view of the energy transfer device of Fig. 9, according to one embodiment of the invention.

Detailed Description

One embodiment of the present invention is directed to methods and apparatus for transferring energy across a boundary, for example, from a position external to a closed system, or "body," to a position internal to the body. The transferred energy may be used to provide power to a device located internal to the body.

According to one aspect of this embodiment, the energy received internal to the body, and hence the power provided to the internal device, is not significantly affected by appreciable changes in the relative positions between an external energy transmitter and an internal energy receiver on opposite sides of a boundary. Stated differently, more than nominal (or trivial) axial or lateral displacements of one or both of the energy transmitter and receiver do not result in significant variations in the power provided to the internal device. In this manner, a sufficiently stable power may be provided to the internal device,

notwithstanding more than nominal movement of one or both of the energy transmitter and the energy receiver.

Another aspect of the present invention relates to energy transfer methods and devices for use in connection with the human body. In particular, one embodiment of the invention is directed to a transcutaneous energy transfer (TET) device functioning as a power transformer to transfer power from an external power source to a device implanted in the body.

In one aspect of this embodiment, a TET device according to the invention includes an "oversized" primary winding (coil) affixed in proximity to an exterior surface of the skin, and a secondary winding implanted in the body and aligned with the primary winding. More specifically, according to this embodiment, an area delimited by the primary winding, from which a magnetic field is generated, is at least twice that of an area delimited by the secondary winding of the TET device, through which the secondary winding intercepts or "receives" the magnetic field. The larger area of the oversized primary winding allows a significant displacement between the primary and secondary windings while nonetheless maintaining uniformity of the magnetic field that impinges on the secondary winding. As a result, the secondary winding is capable of providing a sufficiently stable power to the implanted device, notwithstanding more than nominal shifts in the relative positions of the windings.

To the best of Applicant's knowledge, the use of an oversized primary winding in a TET device according to one embodiment of the invention, as introduced above and discussed in greater detail below, is contrary to the teachings and focus of conventional TET device designs. More specifically, conventional TET device designs generally seek to optimize a magnetic coupling between the primary and secondary windings by employing identically-sized or nearly identically-sized windings and limiting a distance separating the windings. In contrast to such conventional techniques, however, the magnetic coupling of a TET device according to one embodiment of the present invention is decreased, rather than optimized, as a result of using an oversized primary winding. Such a decrease in magnetic coupling due to an oversized primary winding is merely a tradeoff, however, for other distinct advantages.

For example, the use of an oversized primary winding in a TET device according to one embodiment of the present invention increases the magnetic field strength at a given axial distance from the primary winding, relative to that of a primary winding having the same or nearly the same size as the secondary winding. Additionally, as discussed above, the larger

area of the oversized primary winding from which the magnetic field is generated permits a more than nominal lateral displacement or misalignment of the secondary winding relative to the primary winding, while nonetheless preserving the uniformity of the magnetic field that impinges on the secondary winding.

The increased strength and area of the magnetic field due to an oversized primary winding increases an "effective operating range" (maximum axial and/or lateral displacement while maintaining a sufficient power output to a load) of a TET device according to one embodiment of the invention as compared to conventional TET devices. The increased effective operating range due to the oversized primary winding may permit, for example, a TET device according to the invention to be used through various objects such as clothing, creams, bandages, medicated ointments, and the like, even though such objects may add appreciably to the distance separating the primary and secondary windings and the degree of shifting that may occur between the windings with patient movement. As a result, a greater degree of patient comfort and flexibility may be afforded by methods and apparatus according to the invention.

While, as discussed above, an oversized primary winding may decrease the magnetic coupling in a TET device according to the invention relative to that of a conventional TET device having similarly-sized windings, in one embodiment such a reduction in magnetic coupling may be compensated in part by configuring the primary and secondary windings as "tuned" circuits. In such a configuration, energy is transferred from the primary winding to the secondary winding at or near a resonant frequency of the tuned circuits. This arrangement can result in a TET device having an energy transfer efficiency (power output/power input) between approximately 75-80%. In one aspect of this embodiment, at an "extreme" misalignment, the primary and secondary windings may be axially or laterally displaced from "typical" operating positions by up to two inches (50 mm), and the secondary winding is nonetheless able to deliver to a load at least 50% of the power capability of the TET device in the typical position.

Fig. 1 is a diagram showing an example of an implementation of a TET device 100 in a human body 90, according to one embodiment of the invention. In Fig. 1, the TET device 100 is employed to transfer energy (or power) from a power source 112 located externally to the body 90 (e.g., strapped to the waist of the patient) to one or more implanted devices 110 internal to the body 90. An implanted device 110 that receives power from the TET device

100 may be, for example, an implanted prosthesis such as a synthetic heart or a circulatory blood pump. Additionally, an implanted device 110 may be a battery that receives power from the TET device 100, for example, to maintain a charge on the battery or to recharge the battery. The implanted battery in turn provides power to one or more implanted prosthesis or other implanted devices.

As shown in Fig. 1, a primary winding 102 of the TET device 100 is positioned externally proximate to the skin 302 of the patient and connected to the power source 112 via a cable 104. A secondary winding 106 of the TET device 100 is implanted within the body 90 of the patient and is connected to the implanted device 110 by a cable 108. Both the internal secondary winding 106 and the implanted device 110 are shown shaded in "phantom" in Fig. 1 for purposes of illustration, as they are located beneath the skin 302 inside the body 90.

In the TET device 100 of Fig. 1, the primary winding 102 and the secondary winding 106 are constructed and arranged such that at least a portion of a magnetic field generated by the primary winding 102 travels through the skin 302 (and perhaps other body tissues or coverings) and impinges upon the secondary winding 106. The portion of the magnetic field intercepted by the secondary winding 106 (and hence the received energy) is converted to an electrical power which is provided to the implanted device 110. Accordingly, the implanted device 110 serves as a "load" for the secondary winding 106.

As can be seen in Fig. 1, according to one embodiment of the invention, the primary winding 102 delimits a larger area than does the secondary winding 106, thereby allowing an appreciable axial and/or lateral displacement between the windings 102 and 106 without significantly affecting the uniformity of the magnetic field impinging upon the secondary winding 106, as discussed above. While the windings 102 and 106 shown in Fig. 1 are illustrated as having a substantially circular shape, the invention is not limited in this respect, and the windings 102 and 106 may have a variety of shapes and geometric configurations, as discussed further below. Additionally, it should be appreciated that the primary and secondary windings are not limited to the relative geometries illustrated in Fig. 1, and that, for example, each of the windings may have a different shape than the other.

Fig. 2 shows a "side" view of the TET device 100 shown in Fig. 1, viewed along the patient's skin 302 (as if the patient were lying on their back, for example). For purposes of illustration in Fig. 2, the skin 302 approximately defines an x-axis 14 in a Cartesian coordinate system. Fig. 2 also shows a z-axis 12 essentially perpendicular to the skin 302.

which serves as a common axis between the primary winding 102 and the secondary winding 106. A y-axis 13 of the Cartesian coordinate system is directed through the page of Fig. 2, representing the direction of the side view. While the primary and secondary windings of Fig. 2 are illustrated as having some thickness in the z-direction, it should be appreciated that the figure is not to drawn to scale, and that in one embodiment the windings are typically planar devices having nominal thicknesses. It should also be appreciated, however, that in other embodiments, one or both of the windings may have a significant dimension along the z-axis shown in Fig. 2, and have a variety of volumetric shapes and relative arrangements.

In one embodiment, the secondary winding 106 may be affixed to a layer of tissue (not shown in Fig. 2) close to an interior surface of the skin 302, and the primary winding 102 may be placed directly on an external surface of the skin 302. Alternatively, as shown in Fig. 2, the primary winding 102 may be placed proximate to an external surface of the skin 302 above one or more intervening layers of material 103 which may be, for example, one or more articles of clothing, an ointment or a cream, one or more bandages, and the like.

Figs. 3 and 4 each is a "top" view (looking down onto the patient of Fig. 1) of an example of a TET device 100 that may be employed in the embodiment shown in Fig. 1. However, it should be appreciated that the invention is not limited to the examples shown in Figs. 3 and 4, as these examples are merely for illustrative purposes. In each of Figs. 3 and 4, the x-axis 14 and the y-axis 13 define a plane that is essentially parallel with the patient's skin 302.

In Fig. 3, the primary winding 102 delimits an approximately circular area 102' having a diameter 24 and a radius 202 (R_1), while the secondary winding 106 delimits an approximately circular area 106' having a diameter 26 and a radius 204 (R_2) which is smaller than the radius 202 (R_1). The ratio of the area 102' to the area 106' in the example of Fig. 3 is given by $(R_1/R_2)^2$. Fig. 3 also shows that, at an optimum relative position, the primary and secondary windings 102 and 106 are essentially "mutually aligned," in that they share a common geometric center through which the z-axis 12 (shown in Fig. 2) passes.

Fig. 4 shows a "top" view similar to Fig. 3 in which the primary winding 102 and the secondary winding 106 delimit areas 102' and 106', respectively, having essentially square shapes. While the sides of the square areas shown in Fig. 4 are essentially parallel to the respective x and y-axes indicated in Fig. 4, it should be appreciated that one or both of the square shaped windings 102 and 106 may be oriented arbitrarily with respect to the x and y-

axes shown in the figure. In Fig. 4, the primary winding 102 has a side dimension 203 (a) and the secondary winding 106 has a side dimension 205 (b) that is smaller than the side dimension 203. The ratio of the area 102′ to the area 106′ in the example of Fig. 4 is given by $(a/b)^2$. Additionally, like Fig. 3, Fig. 4 also shows that, at an optimum relative position, the primary and secondary windings 102 and 106 are essentially "mutually aligned," in that they share a common geometric center through which the z-axis 12 (shown in Fig. 2) passes.

According to one embodiment of the invention, the first area 102′ is at least twice that of the second area 106′. In one aspect of this embodiment, a suitable ratio of the first area 102′ to the second area 106′ delimited by a TET device having arbitrary winding perimeter shapes is in a range of from approximately 2:1 to 80:1. Stated differently, the first area 102′ may be from 2 to 80 times larger than the second area 106′. In another aspect of this embodiment, the first area may be at least 4 times larger than the second area. In yet other aspects of this embodiment, the first area may be at least 9 times larger than the second area, at least 16 times larger than the second area, at least 36 times larger than the second area, and at least 80 times larger than the second area. In particular, according to one embodiment of the invention, the first area 102′ may be in a range of from approximately 7 to 30 square inches and the second area 106′ may be in a range of from approximately 2 to 7 square inches, as long as the ratio of the first area to the second area is at least 2:1.

For example, with reference to Fig. 3 in which the primary and secondary windings delimit areas having essentially circular shapes, the first area 102' may have a diameter 24 in a range of from approximately 3 to 6 inches and the second area 106' may have a diameter 26 in a range of from approximately 1 to 3 inches. More specifically, according to one aspect of this embodiment, the first area 102' may have a diameter 24 in a range of from approximately 4 to 5.5 inches and the second area 106' may have a diameter 26 in a range of from approximately 2 to 2.75 inches.

In another embodiment, the first area 102' may have a diameter 24 that is greater than 3.5 inches. In yet another embodiment, the first area 102' has a diameter of approximately 5.5 inches and the second area 106' has a diameter of approximately 2.5 inches. In general, examples of ratios of the diameter of the first area to the diameter of the second area suitable for purposes of embodiments of the invention involving essentially circular first and second areas include, but are not limited to. 1.5:1, 2:1, 3:1, 3.5:1, 4:1, 6:1, and 9:1. The significance of the relative dimensions of the primary and secondary windings is discussed in greater detail further below.

A brief discussion of magnetic field theory will facilitate a fuller understanding of the inventive concepts behind various aspects of the present invention. Fig. 5 shows a three-dimensional view of the primary winding 102 of the TET device 100, in a Cartesian coordinate system defined by the x-axis 14, the y-axis 13, and the z-axis 12. In the present discussion, the primary winding 102 illustrated in Fig. 5 may be viewed as a generic example of a winding independent from the TET device 100, for purposes of explaining some principles of magnetic field theory. Additionally, for purposes of the present discussion, the winding 102 of Fig. 5 is idealized to have a single winding turn to simplify the mathematical relationships discussed below. It should be appreciated, however, that windings according to various embodiments of the invention may have a number of winding turns. Nonetheless, the following discussion pertaining to a single turn winding is useful for illustrating some relevant concepts related to the present invention.

In Fig. 5, the winding 102 delimits an approximately circular area 102′ which defines a plane 300. The x-axis 14 and the y-axis 13 pass through the plane 300, and each of the x, y, and z-axes pass through a geometric center 10 of the area 102′. The area 102′ has a radius 202 (*R*). A current 15 (*i*) flowing through the winding 102 creates a magnetic field *H*, represented in Fig. 5 as lines of magnetic flux 30, according to the relationship

$$H = \frac{1}{4\pi} \oint \frac{\bar{r} \times \overline{di}}{\left|\bar{r}\right|^3}, \tag{1}$$

where *di* is a current element, and *r* is a vector from the current element to an observation point at an arbitrary position in the coordinate system. Fig. 6 is a two-dimensional "side" view looking along the y-axis of Fig. 5, which shows in part that the magnetic field generated by the current *i* flowing through the winding 102 according to Eq. (1) may be represented by a series of approximately elliptically shaped concentric magnetic flux lines 30, having increasing diameters as the observation point increases in distance from the winding 102.

As a practical and useful approximation, the magnetic flux lines 30 shown in Fig. 6 may be viewed as "straightening out" as one approaches the center of the area 102′ delimited by the winding 102 (i.e., along the z-axis 12), which constitutes the farthest point within the area 102′ from the current *i* flowing in the winding. In this manner, the magnetic field generated by the winding 102 within the area 102' can be viewed as a number of essentially

straight magnetic flux lines 30 forming a cylindrical profile parallel to and surrounding the z-axis 12, as shown in Fig. 5.

Fig. 7 is a graph showing two plots 502 and 504 of relative magnetic field strength as a function of distance along the z-axis 12 from the plane 300 of the winding 102 shown in Figs. 5 and 6, for a given current i flowing through the single turn winding. For such an "axial" displacement from the winding plane 300 along the z-axis 12, Eq. (1) reduces to the relationship

$$H = \frac{iR^2}{2(R^2 + Z^2)^{\frac{3}{2}}} \quad , \qquad (2)$$

where R is the radius 202 of the area 102' and Z is the axial displacement from the plane 300 along the z-axis 12. In Fig. 7. the horizontal axis of the graph shows the axial displacement Z from the winding plane in units of the radius R of a given winding. The plot 502 in Fig. 7 represents Eq. (2) using a winding radius of R, whereas the plot 504 represents Eq. (2) using a winding radius of $2R$ through which the same magnitude of current flows. Hence, Fig. 7 compares the relative strengths of a magnetic field at an axial observation point from the plane of a winding, for two differently sized windings each having a single winding turn.

Fig. 7 shows that at an observation point 10′ at an axial distance $Z = R$ along the z-axis 12 from the plane 300 of a winding having a radius R, the magnetic field strength drops to a relative value of approximately .35, as indicated by the plot 502. Fig. 7 also shows that at the same axial distance R, the relative magnetic field strength from a larger winding having a radius of $2R$ is approximately .7, as shown by the plot 504. Thus, the graph of Fig. 7 demonstrates that by doubling the radius (or diameter) of a winding, the "effective axial operating range" may be in principle doubled, i.e., a larger winding area 102′ provides a greater effective axial operating range relative to a smaller sized winding.

Fig. 8 is a graph similar to Fig. 7, showing two plots 506 and 508 representing the relative magnetic field strength for a lateral displacement from the center axis of a given winding, at an axial distance $Z = R$ from the winding plane 300. With reference again to Fig. 5, the horizontal axis of the graph of Fig. 8 refers to a lateral displacement along the x′-axis 14′. which is perpendicular to the z-axis 12 at a distance from the winding plane 300 equal to the radius R of the winding area 102′. The plot 506 in the graph of Fig. 8 represents Eq. (1) evaluated at a number of observation points along the x′-axis. where the vector $\bar{r}$ in Eq. (1) is determined based upon a winding radius R, and the plot 508 is evaluated similarly for a

winding radius of $2R$. Like the graph of Fig. 7, Fig. 8 indicates that windings delimiting larger areas generally have a greater effective lateral operating range relative to smaller windings. Accordingly, both Figs. 7 and 8 demonstrate the advantages of using an oversized primary winding in a TET device according to one embodiment of the invention to increase an effective operating range of the device.

Figs. 9 and 10 are more detailed three-dimensional diagrams of the TET device 100 shown in Figs. 1, 2, and 3, illustrating two different positions of the primary winding 102 relative to the secondary winding 106. As discussed above, the primary winding 102 has an essentially planar shape and defines a first plane which includes the area 102′ ("above" the skin 302), as indicated in Fig. 9 by the x_1-axis 14 and the y-axis 13. In Fig. 9, the x_1-axis and the y-axis intersect at a geometric center 10 of the primary winding 102, which serves as a reference for the position of the primary winding 102 in space. Similarly, in Figs. 9 and 10, the secondary winding 106 has an essentially planar shape and defines a second plane including the area 106′ ("below" the skin 302). A geometric center 20 of the secondary winding 106 serves as a reference for the position of the secondary winding in space. An x_2-axis 16 essentially parallel to the x_1-axis 14 passes through the second plane defined by the secondary winding 106. Hence, the primary and secondary windings are essentially parallel and are separated by a normal or axial distance 18 along the z-axis 12.

Fig. 9 shows an "optimum" alignment for the primary and secondary windings. In particular, the respective positions of the primary winding 102 and the secondary winding 106, as indicated by their respective geometric centers 10 and 20, are such that the z-axis 12 serves as a common axis which passes through each geometric center; namely, in the example of Fig. 9 showing essentially circular windings, the primary winding 102 and the secondary winding 106 are concentrically aligned. A distance corresponding to the difference between the respective radii 202 and 204 (R_1 - R_2) of the primary and secondary windings is indicated in Fig. 9 by the reference character 25.

As discussed above, the primary winding 102 of the TET device 100 shown in Fig. 9 transmits energy in the form of magnetic field, which may be represented by a cylindrical profile of magnetic flux lines 30. The secondary winding 106 intercepts (receives) at least a portion of the magnetic field transmitted by the primary winding 102. In one embodiment, the magnetic field (or energy) received by the secondary winding 106 is not significantly affected by a change in the normal (axial) distance 18 between the relative positions of the primary and secondary windings, wherein the change amounts to more than a nominal change

in the axial distance 18. In particular, according to one embodiment of the invention, an electrical power supplied by the secondary winding 106, based on the energy in the portion of the magnetic field received by the secondary winding, remains sufficiently stable notwithstanding a more than nominal change in the axial distance 18, such that satisfactory operation of a device receiving power from the secondary winding 106 (e.g., the implanted device 110 shown in Fig. 1) is maintained.

As discussed above in connection with Fig. 7, the effective axial operating range of a given primary winding 102 is a function, in part, of the radius of the winding. Hence, the radius of the primary winding 102 of Fig. 9 may be selected based in part upon a "typical" axial distance 18 expected during normal operation and use of the TET device 100 (e.g., with a patient having an implanted device), and based on the degree of desired stability of power supplied by the secondary winding 106 as a result of some maximum expected change in the axial distance 18, using Eqs. (1) or (2) and the plots of Fig. 7 as a guideline.

For example, in one embodiment, the primary winding 102 and the secondary winding 106 may be constructed and arranged such that sufficient power is provided by the secondary winding at a "typical" axial distance 18 of greater than approximately .25 inches (approximately 6 millimeters). In one aspect of this embodiment, the secondary winding 106 may be constructed and arranged such that sufficient power is provided by the secondary winding at a "typical" axial distance 18 in a range of from approximately .5 to 1 inch (approximately 13-26 mm).

For purposes of the present discussion, a "nominal" change in the axial distance refers to a minor axial displacement that amounts to less than approximately .15 inches (approximately 4 millimeters). Hence, a "more than nominal" change in the typical axial distance refers to a change of greater than .15 inches in the axial distance.

Alternatively, a "more than nominal change" in the axial distance may be viewed in terms of an axial displacement that amounts to more than approximately 60-70% of the typical axial distance. For example, using a typical axial distance of at least .25 inches for purposes of illustration, a change of at least .15 inches amounts to a 60% change in the axial distance. Similarly, using a typical axial distance of at least .5 inches for purposes of illustration, a change of at least .3 inches amounts to a 60% change in the axial distance. It should be appreciated, however, that interpreting nominal changes in the axial distance in terms of a percent of a typical axial distance provides merely one example of a convenient measure of nominal changes, and that the invention is not necessarily limited in this respect.

Rather, as discussed above, in general a "more than nominal" change in the typical axial distance refers to a change of greater than .15 inches in the axial distance.

Additionally, for purposes of the present discussion, a "sufficiently stable" power supplied by (or energy received by) the secondary winding 106 refers to a variation in the peak electrical power provided to a load (or in the energy received by the secondary winding) of less than 50%. For example, in one embodiment of the TET device 100 shown in Fig. 9, the energy received by the secondary winding 106 (and hence the power supplied by the secondary winding 106) does not decrease by more than 50% due to a change (in particular, an increase) of more than .15 inches in the axial distance 18. According to yet another embodiment of the invention, the typical axial distance may be increased by significantly more than 60-70% of the typical axial distance (e.g., up to 200%) without a corresponding decrease of more than 50% in the power supplied by the secondary winding.

For example, in one embodiment, as discussed above, the primary winding 102 and the secondary winding 106 may be constructed and arranged such that sufficient power is provided by the secondary winding at a "typical" axial distance 18 in a range of from approximately .5 to 1 inch (approximately 13-26 mm). In one aspect of this embodiment, the primary and secondary windings may be constructed and arranged such that the power is not significantly affected (e.g., varies by less than 50 %) due to changes in the typical axial distance 18 of from .25 to 1 inch (as much as a 200% change in the axial distance), thus giving rise to an effective axial operating range of up to approximately 2 inches (50 mm).

Fig. 10 is a diagram similar to that of Fig. 9, in which the secondary winding 106 has been laterally displaced by a lateral distance 22 from the z-axis 12, along the x_2-axis 16. In Fig. 10, the geometric center of the secondary winding 106 following the lateral displacement is indicated by the reference character 20b, whereas the "former" geometric center of the secondary winding 106 prior to the lateral displacement is indicated by the reference character 20a.

As in Fig. 9, to accommodate the lateral displacement shown in Fig. 10, the primary winding 102 and the secondary winding 106 of the TET device 100 are constructed and arranged such that the energy received by the secondary winding 106 is not significantly affected by a more than nominal lateral displacement between the primary and secondary windings, as indicated by the distance 22, at a typical axial distance 18. While in Fig. 10 only the secondary winding 106 is shown as having changed position from the arrangement shown in Fig. 9, it should be appreciated that the position of one or both of the primary winding 102

and the secondary winding 106 may be changed in either direction along the x_1-axis 14 and the x_2-axis 16, respectively, as well as in either direction parallel to the y-axis 13, to create a lateral displacement between the two windings corresponding to the lateral distance 22.

In one embodiment, an oversized primary winding 102 as shown in Figs. 9 and 10 insures that the energy received by the secondary winding 106 is not significantly affected by a more than nominal lateral displacement between the primary and secondary windings 102 and 106. As discussed above in connection with axial displacement, due to the oversized primary winding 102, an electrical power supplied by the secondary winding 106, based on the energy in the portion of the magnetic field received by the secondary winding, remains sufficiently stable notwithstanding a lateral displacement corresponding to the lateral distance 22, such that satisfactory operation of a device receiving power from the secondary winding 106 (e.g., the implanted device 110 shown in Fig. 1) is maintained. For purposes of the present discussion, a nominal lateral displacement refers to minor lateral displacements between the respective geometric centers of the areas delimited by the windings amounting to less than approximately .25 inches (approximately 13 mm). Accordingly, "more than nominal" lateral displacements refer to lateral displacements amounting to more than approximately .25 inches.

In general, as long as the lateral displacement distance 22 shown in Fig. 10 is equal to or less than the distance 25 shown in Fig. 9, corresponding to the difference in the winding radii 202 and 204 (R_1 - R_2), the secondary winding 106 intercepts an essentially constant or uniform magnetic flux from the primary winding 102. This situation may be viewed conceptually by imagining the secondary winding 106 freely moving anywhere in its x-y plane within the confines of the cylindrical profile of magnetic flux lines 30 generated by the primary winding 102. As long as the secondary winding 106 remains within the confines of the cylindrical profile of magnetic flux lines, the power supplied by the secondary winding 106 to a device remains essentially constant.

In one embodiment, the primary and secondary windings of the TET device 100 shown in Figs. 9 and 10 may be constructed and arranged such that the energy received by the secondary winding 106 remains essentially constant, notwithstanding lateral displacements constituting a lateral distance 22 of between .5 and 2 inches (12-50 mm). In general, the maximum lateral displacement range in which constant received energy may be maintained is given by the distance 25, and hence is a function of the respective radii 202 and 204 of the windings 102 and 106. In another embodiment, the primary and secondary

windings of the TET device 100 shown in Figs. 9 and 10 may be constructed and arranged such that for a maximum expected lateral displacement (which in some cases may exceed the distance 25 indicated in Fig. 9) the secondary winding 106 nonetheless intercepts a sufficient magnetic field so as to supply no less than 50% of its full power capability (e.g., when the primary and secondary windings are "optimally" aligned, as shown in Fig. 9) to a device constituting a load on the secondary winding.

The foregoing discussion with respect to axial and lateral displacement of the primary and secondary windings of a TET device according to one embodiment of the invention is for purposes of illustrating some practical and simplified concepts relevant to some aspects of the present invention, and is not intended to be limiting or theoretically exhaustive. In general. it should be appreciated from the foregoing discussion that as the axial distance between the primary and secondary windings increases, the maximum lateral displacement for which an essentially constant magnetic flux may be received through the secondary winding decreases. In particular, according to one embodiment of the invention, at an "extreme" axial displacement for concentrically aligned primary and secondary windings (at which the secondary winding is capable of providing approximately 50% power), essentially no lateral displacement can be tolerated without further decrease in output power.

Following is a brief summary of the theory of operation of the TET device 100 shown in Figs. 9 and 10. As discussed above in connection with Fig. 5, a magnetic field generated by the current i flowing through the primary winding 102 may be approximated as a cylindrical profile of magnetic flux lines 30 emanating from the plane of the primary winding 102. The density B (in Webers/m^2) of the magnetic field represented by the cylinder of magnetic flux lines 30 may be given approximately by the expression

$$B \approx \mu\left[\frac{N_1\, i}{2R_1}\right] , \qquad (3)$$

where μ is the "permeability" of the material through which the magnetic field passes (e.g., skin, etc.), N_1 is the number of winding turns in the primary winding 102, i is the current in the primary winding 102, and R_1 is the radius 202 of the primary winding 102.

Due to the smaller area delimited by the secondary winding 106, the secondary winding intercepts only some of the magnetic flux lines 30 and, hence, only a portion of the magnetic field generated by the primary winding 102. A magnetic flux $\varphi_{2,1}$ (in Webers)

intercepted by the secondary winding 106 due to a magnetic field generated by the primary winding may be expressed in terms of the density B of the magnetic field multiplied by the area 106′ delimited by the secondary winding 106, as

$$\phi_{2,1} = BA_2 \approx \mu\left[\frac{N_1 i}{2R_1}\right]\left[\pi R_2^{\ 2}\right], \tag{4}$$

where A_2 is the area 106′ delimited by the secondary winding 106, and R_2 is the radius 204 of the secondary winding 106.

A time-varying or alternating current $i(t)$ in the primary winding 102 in turn generates a time-varying magnetic field which results in a time-varying flux $\varphi_{2,1}(t)$ intercepted by the secondary winding 106. Such a time-varying flux induces a voltage $v(t)$ across the secondary winding 106 according to Faraday's law, given as

$$v(t) = -N_2\left(\frac{d\phi_{2,1}(t)}{dt}\right) \quad , \tag{5}$$

where N_2 is the number of winding turns in the secondary winding. The voltage $v(t)$ induced across the secondary winding 106 provides a source of electrical power to a load connected to the secondary winding. As can be seen from Eq. (5), the stability of the voltage in the secondary winding 106 (and hence the power supplied to a load by the secondary winding 106) depends upon the stability of the magnetic flux $\varphi_{2,1}(t)$ intercepted by the secondary winding 106.

In view of the foregoing, and as discussed above in connection with Figs. 9 and 10, it should be appreciated that the larger size of the primary winding 102 with respect to the secondary winding 106 provides a cylindrical profile of magnetic flux lines, within which the secondary winding may move while nonetheless intercepting a stable magnetic flux $\varphi_{2,1}(t)$ having an essentially constant amplitude. Once the secondary winding 106 is laterally displaced beyond the confines of the cylindrical profile of magnetic flux lines (determined by the position of the primary winding 102), the flux intercepted by the secondary winding 106 begins to decrease (the amplitude of the time-varying flux in Eq. (5) begins to decrease). As a result, the voltage across the secondary winding according to Eq. (5) begins to decrease.

resulting in a corresponding decrease in power supplied by the secondary winding 106 to a load.

The TET device 100 shown in Figs. 1, 2, 3, 9, and 10 may provide several advantages particularly to prosthetic implant patients, as well as in a variety of other applications. Unlike conventional TET devices in which a primary winding is constrained to be located as close to the skin as possible, the TET device 100 has an increased effective operating range and permits an appreciable displacement between the primary and secondary windings, thereby affording greater flexibility and a greater freedom of movement for the patient. For example, the primary winding 102 of the TET device 100 may be attached, for example, to an article of clothing or placed in a pocket without adversely affecting the power supplied to an implanted device. Additionally, various medicated ointments, protective creams or cushions, bandages, and the like may be placed between the primary winding 102 and the patient's skin 302 to prevent and/or treat discomfort or irritation to the skin without adversely affecting the power supplied to an implanted device.

In selecting appropriate parameters (e.g., the relative winding sizes, the number of winding turns for primary and secondary windings) for a particular application employing a TET device 100 according to various embodiments of the invention, the power requirements of one or more devices to receive power from the secondary winding, and the amount of displacement which is likely to occur between the primary and secondary windings during normal use (e.g., with a patient having one or more implanted devices), are taken into consideration. For example, for applications in which the primary and secondary windings are to be rigidly attached to a boundary of a system (e.g., the skin of the body) and maintained in predetermined positions, the amount of displacement which is likely to occur between the windings is low. Accordingly, the respective areas delimited by the primary and secondary windings may be selected such that the ratio of the areas is closer to two, thereby increasing the magnetic coupling and hence the energy transfer efficiency of the TET device.

Alternatively, for other applications, the primary and/or secondary winding may not be so rigidly attached to a boundary (e.g., the primary winding may be attached to an article of clothing). In this case, some occasional displacement due to shifting of the primary winding from a position in which the windings are mutually aligned (e.g., Fig. 9) is likely. Accordingly, the respective areas delimited by the primary and secondary windings may be selected such that the ratio of the areas is sufficient to allow for greater displacement without variation in the power supplied by the secondary winding. For example, in one embodiment

involving essentially circular planar windings, the primary winding may have a diameter 24 of between 3 and 6 inches (75-150 mm) and the secondary winding 102 may have a diameter 26 of between 1 and 3 inches (25-75 mm). A primary winding larger than 6 inches may become too bulky and uncomfortable to wear for a patient, while a primary winding smaller than 3 inches may provide too small of an effective operating range. Similarly, a secondary winding larger than 3 inches may be excessively large to implant in a patient, while a secondary winding smaller than 1 inch may not provide sufficient power to a device, as discussed further below.

As discussed above, one consequence of employing an oversized primary winding 102 is that the magnetic coupling of the TET device 100 is weaker than the magnetic coupling of identically or nearly identically-sized windings. This may be viewed conceptually in Figs. 9 and 10, where it can be seen that some of the magnetic flux lines 30 do not intercept the secondary winding 106, thereby not using a region of the space where theoretically power could be transferred to a secondary winding having a size closer to that of the primary winding. Additionally, a smaller secondary winding is capable of transferring less power to a device than would a larger secondary winding, based on an equivalent energy received by the secondary winding.

In view of the foregoing, an appropriate number of winding turns for the respective primary and secondary windings may be selected based on an anticipated size (area) of the windings, power requirements of the load, and voltage and current operating conditions of both the external power supply supplying power to the primary winding and the load. In particular, the primary and secondary windings may be configured as "tuned" circuits, wherein the energy is transferred between the primary and secondary windings at or near a particular resonant frequency that is amplified by the secondary tuned circuit, to compensate for a lower energy transfer efficiency of the TET device due to an oversized primary winding.

Fig. 11 is a "side" view similar to that of Fig. 2 of a TET device 100 according to one embodiment of the invention. Fig. 11 shows the primary winding 102 and the secondary winding 106 in greater detail. As shown in the embodiment of Fig. 11. the primary winding 102 may include from 3 to 5 winding turns 402 in an essentially planar configuration, and the secondary winding 106 may include from 12 to 16 winding turns 404 arranged in multiple layers as a "squashed helix."

According to one embodiment of the invention, design parameters of the primary and secondary windings shown in Fig. 11 may be determined somewhat empirically using basic

transformer operating principles, based on the geometry and operating conditions of the TET device. For example, first a target resonant frequency may be selected to transfer energy from the primary winding 102 to the secondary winding 106. The target resonant frequency may be based on an approximate area delimited by the secondary winding which is suitable for human use, and a suitably small capacitor (not shown in Fig. 11) for the resonant ("tuned") circuit that may be contained within the confines of the area 106' delimited by the secondary winding. In one aspect of this embodiment, a secondary winding delimiting an area 106' of approximately 5 square inches (e.g., a circular area having a diameter of approximately 2.5 inches) can accommodate a capacitor having a capacitance as low as approximately 10 nanofarads (nF). In another more general aspect of this embodiment, the capacitance of the capacitor for the secondary winding tuned circuit is preferably as low as possible given the available volume for the capacitor to occupy, so that RF losses are sufficiently low.

Based on a capacitance of the capacitor and the selected target resonant frequency, a target inductance for the secondary winding 106 can be determined. For example, in one embodiment, a target resonant frequency of approximately 300 kHz and a capacitance of 10 nF results in a target secondary winding inductance of approximately 30 μH. Such a target inductance may be achieved in a secondary winding delimiting an approximately circular area having a diameter of approximately 2.5 inches using approximately 14 winding turns 404. It should be appreciated that according to other embodiments involving different secondary winding geometries and sizes, the number of winding turns 404 required to achieve the target inductance varies accordingly.

Once the number of secondary winding turns 404 is determined, the number of primary winding turns 402 may be determined based in part on the voltage requirements of the load and the output voltage of the external power supply that provides power to the primary winding. In particular, a "turns ratio" between the primary and secondary windings determines in part a corresponding voltage ratio between a voltage across the primary winding and a voltage across the secondary winding.

In one aspect of this embodiment, the external power supply has an operating voltage in a range of from 15-30 volts, and the load on the secondary winding similarly has an operating voltage in a range of from 15-30 volts. However, due to the "oversized" primary winding and a corresponding low energy transfer efficiency (i.e., some of the magnetic flux generated by the primary winding is "unused" by the secondary winding), a high turns ratio

(secondary winding to primary winding) is desirable in this aspect to achieve a high voltage transfer ratio so as to compensate in part for the low energy transfer efficiency.

In particular, in one aspect of this embodiment, for a secondary winding having approximately 14 winding turns 404, an oversized primary winding delimiting an approximately circular area 102' having a diameter of approximately 5.5 inches is constructed to have approximately 4 winding turns 402. Given a primary winding voltage of approximately 15-30 volts, such a turns ratio results in a secondary winding voltage in approximately the same range, notwithstanding a turns ratio of higher than one. The resulting inductance of such a primary winding is approximately 3 μH. In another aspect of this embodiment, the number of primary winding turns 402 may be determined empirically from an iterative process until a desired secondary winding voltage is achieved.

Once the inductance of the primary winding is determined based on the number of winding turns 402 and the winding geometry, the primary tuned circuit capacitance is chosen such that the primary resonant frequency and the secondary resonant frequency are approximately equal. Accordingly, based on a primary winding inductance of 3 μH, a primary (and secondary) resonant frequency of 300 kHz in the present example corresponds to a primary capacitance of approximately 100 nF.

Using parameters similar to those outlined above, a power output of 15 to 50 watts at a voltage of 15 to 30 volts and a current of 2 to 3 amps may be supplied by the secondary winding 106 to one or more devices such as the implanted device 110 shown in Fig. 1 over the effective operating range of the TET device 100. For an external power source 112 coupled to the primary winding 102, as shown in Fig. 1, and providing a power output in a range of from approximately 20 to 60 watts, a TET device having parameters similar to those outlined above accordingly is capable of an energy transfer efficiency (power output/power input) of as high as 75-80%.

While numerous concepts related to the transfer of energy across a boundary have been discussed above in the context of a TET device for use with a human patient having one or more implanted prostheses or other devices, the above-discussed aspects of the present invention can be implemented in any of numerous ways, as the invention is not limited to any particular manner of implementation. For example, the concepts of energy transfer across a boundary discussed herein may be applied to a variety of living or inanimate systems delimited by various types of boundaries, in which a device internally located within the system requires power from an external power source.

Having thus described at least one illustrative embodiment of the present invention, various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alternations, modifications, and improvements are intended to be within the spirit and scope of the invention. Accordingly, the foregoing description is by way of example only and is not intended to be limiting. The invention is limited only as defined in the following claims and equivalents thereof.

What is claimed is:

CLAIMS

1. An apparatus, comprising:

a first energy transfer element to transmit energy, the first energy transfer element delimiting a first area through which the energy is transmitted; and

a second energy transfer element to receive at least a portion of the energy, the second energy transfer element delimiting a second area through which at least a portion of the energy is received as received energy,

wherein the first area is at least twice as large as the second area.

2. The apparatus of claim 1, wherein the first area is at least four times as large as the second area.

3. The apparatus of claim 1, wherein the first area is at least nine times as large as the second area.

4. The apparatus of claim 1, wherein the first area is at least sixteen times as large as the second area.

5. The apparatus of claim 1, wherein the first area is at least thirty-six times as large as the second area.

6. The apparatus of claim 1, wherein a ratio of the first area to the second area is in a range of from approximately 2:1 to 80:1.

7. The apparatus of claim 1, wherein the second energy transfer element is constructed and arranged so as to provide an output power to a load based on the received energy.

8. The apparatus of claim 1, wherein:

the apparatus is a transformer;

the first energy transfer element is a primary winding of the transformer;

the second energy transfer element is a secondary winding of the transformer;

the primary winding transmits the energy as a first magnetic flux while an input power is applied to the primary winding;

the secondary winding receives the received energy as a second magnetic flux; and

the secondary winding is constructed and arranged so as to provide an output electrical power to a load based on the second magnetic flux.

9. The apparatus of claim 8, wherein the primary winding and the secondary winding are mechanically separable from each other and are not permanently coupled by a solid structure.

10. The apparatus of claim 8, wherein the transformer does not include a core that structurally couples the primary winding and the secondary winding.

11. The apparatus of claim 8, wherein the secondary winding is constructed and arranged so as to be implantable in a body.

12. The apparatus of claim 11, wherein the primary winding is constructed and arranged so as to be affixed externally to the body to form an energy transfer device with an implanted secondary winding.

13. The apparatus of claim 12, wherein:

the body is a human body; and

the energy transfer device is a transcutaneous energy transfer device.

14. The apparatus of claim 12, wherein the primary and secondary winding are constructed and arranged such that while the input power is applied to the primary winding, the second magnetic flux received by the secondary winding is not significantly affected by a more than nominal spatial displacement of at least one of the primary winding and the secondary winding.

15. The apparatus of claim 12, wherein the primary and secondary winding are constructed and arranged such that while the input power is applied to the primary winding, the output electrical power provided to the load by the secondary winding is not

significantly affected by a more than nominal spatial displacement of at least one of the primary winding and the secondary winding.

16. The apparatus of claim 12, wherein the primary winding and the secondary winding each has an essentially planar shape.

17. The apparatus of claim 16, wherein the primary winding includes from 3 to 5 winding turns.

18. The apparatus of claim 16, wherein the secondary winding includes from 12 to 16 winding turns.

19. The apparatus of claim 16, wherein the first area is in a range of from approximately 7 to 30 square inches.

20. The apparatus of claim 16, wherein the second area is in a range of from approximately 2 to 7 square inches.

21. The apparatus of claim 16, wherein:

the primary winding includes from 3 to 5 winding turns;

the secondary winding includes from 12 to 16 winding turns;

the first areas is in a range of from approximately 7 to 30 square inches; and

the second area is in a range of from approximately 2 to 7 square inches.

22. The apparatus of claim 16, wherein the primary winding and the secondary winding each has an approximately circular shape.

23. The apparatus of claim 22, wherein:

the primary winding has a diameter in a range of from approximately 3 inches to 6 inches; and

the secondary winding has a diameter in a range of from approximately 1 inch to 3 inches.

24. The apparatus of claim 22, wherein:

the primary winding has a diameter in a range of from approximately 4 inches to 5.5 inches; and

the secondary winding has a diameter in a range of from approximately 2 inches to 2.75 inches.

25. The apparatus of claim 12, wherein the secondary winding is constructed and arranged so as to be capable of providing the electrical power in a range of from approximately 15 to 50 watts.

26. The apparatus of claim 25. wherein the secondary winding is constructed and arranged so as to be capable of providing an output voltage in a range of from approximately 15 to 30 volts.

27. The apparatus of claim 25, wherein the secondary winding is constructed and arranged so as to be capable of providing an output current in a range of from approximately 2 to 3 amperes.

28. An apparatus, comprising:

a first energy transfer element to transmit energy, the first energy transfer element located at a first position on a first side of a boundary; and

a second energy transfer element located at a second position on a second side of a boundary to receive at least a portion of the energy transmitted by the first energy transfer element as received energy,

wherein the first and second energy transfer elements are constructed and arranged such that the received energy is not significantly affected by a more than nominal change in at least one of the first position and the second position.

29. The apparatus of claim 28, wherein the received energy remains essentially constant notwithstanding the change in at least one of the first position and the second position.

30. The apparatus of claim 28, wherein the received energy does not decrease by more than 50% due to the change in at least one of the first position and the second position.

31. The apparatus of claim 28, wherein the second energy transfer element is constructed and arranged so as to provide power to a load based on the received energy.

32. The apparatus of claim 28, wherein:

the first energy transfer element transmits a magnetic field to transmit the energy; and

the second energy transfer element receives at least a portion of the magnetic field as the received energy.

33. The apparatus of claim 32, wherein a magnetic flux through the second energy transfer element is not significantly affected by the change in at least one of the first position and the second position.

34. The apparatus of claim 28, wherein:

a common axis passes through both the first and second energy transfer elements; and

the received energy is not significantly affected by a more than nominal lateral displacement of at least one of the first and second energy transfer elements from the first and second positions, respectively, the lateral displacement being essentially nonparallel to the common axis.

35. The apparatus of claim 28, wherein:

the first transfer element delimits a first area that defines a first plane at the first position; and

the second transfer element delimits a second area that defines a second plane at the second position, the second plane being essentially parallel to the first plane.

36. The apparatus of claim 35, wherein the received energy is not significantly affected by a more than nominal change in an axial distance between the first and second positions, the axial distance being essentially perpendicular to the first and second planes.

37. The apparatus of claim 36. wherein:

the axial distance is at least approximately .25 inches;

the change in the axial distance is greater than .15 inches: and

a variation of the received energy is less than approximately 50 %.

38. The apparatus of claim 36, wherein:

the axial distance is at least approximately .25 inches;

the change in the axial distance is in a range of from approximately .25 inches to 1.5 inches; and

a variation of the received energy is less than approximately 50 %.

39. The apparatus of claim 36, wherein the axial distance is at least approximately .5 inches.

40. The apparatus of claim 39, wherein:

the change in the axial distance is in a range of from approximately .5 inches to 1.5 inches; and

a variation of the received energy is less than approximately 50 %.

41. The apparatus of claim 36, wherein:

the change in the axial distance is greater than 60% of the axial distance; and

a variation of the received energy is less than approximately 50 %.

42. The apparatus of claim 36, wherein:

the change in the axial distance is in a range of from approximately 100 % to 200% of the axial distance; and

a variation of the received energy is less than approximately 50%.

43. The apparatus of claim 35, wherein:

a common axis passes through both the first and second areas, the common axis being essentially perpendicular to the first and second planes; and

the received energy is not significantly affected by a more than nominal lateral displacement of at least one of the first and second energy transfer elements from the first and second positions, respectively, the lateral displacement being essentially perpendicular to the common axis.

44. The apparatus of claim 43, wherein:

the lateral displacement is in a range of from approximately .25 inches to 2 inches; and

a variation in the received energy is less than approximately 50 %.

45. The apparatus of claim 43, wherein the received energy is not significantly affected by a more than nominal change in an axial distance between the first and second positions, the axial distance being essentially perpendicular to the first and second planes.

46. The apparatus of claim 45, wherein:

the axial distance is at least approximately .25 inches;

the change in the axial distance is greater than approximately .15 inches;

the lateral displacement is greater than approximately .25 inches; and

a variation in the received energy is less than approximately 50 %.

47. The apparatus of claim 45, wherein:

the axial distance is at least approximately .5 inches;

the change in the axial distance is greater than approximately .15 inches:

the lateral displacement is greater than approximately .25 inches; and

a variation in the received energy is less than approximately 50 %.

48. The apparatus of claim 35, wherein:

the first area has a first geometric center in the first plane;

the second area has a second geometric center in the second plane; and

a common axis perpendicular to both the first and second planes passes through both the first geometric center and the second geometric center when the first and second energy transfer elements are in the first and second positions, respectively.

49. The apparatus of claim 48, wherein the received energy remains essentially constant notwithstanding a lateral displacement of at least one of the first and second energy elements, the lateral displacement being essentially perpendicular to the common axis.

50. The apparatus of claim 49, wherein the lateral displacement is such that a lateral distance between the first geometric center and the second geometric center is at least .5 inches.

51. The apparatus of claim 49, wherein the lateral displacement is such that a lateral distance between the first geometric center and the second geometric center is at least 1 inch.

52. The apparatus of claim 49, wherein the lateral displacement is such that a lateral distance between the first geometric center and the second geometric center is at least 2 inches.

53. The apparatus of claim 35, wherein the first area is at least twice as large as the second area.

54. The apparatus of claim 53, wherein the first area has an approximately circular shape and has a diameter in a range of from approximately 3 inches to 6 inches in the first plane.

55. The apparatus of claim 54, wherein the second area has an approximately circular shape and has a diameter in a range of from approximately 1 inch to 3 inches in the second plane.

56. The apparatus of claim 53, wherein the first area has an approximately circular shape and has a diameter in a range of from approximately 4 inches to 5.5 inches in the first plane.

57. The apparatus of claim 56, wherein the second area has an approximately circular shape and has a diameter in a range of from approximately 2 inches to 2.75 inches in the second plane.

58. A method of transferring energy, comprising acts of:

transmitting the energy from a first area having a first position on a first side of a boundary; and

receiving at least a portion of the energy as received energy in a second area having a second position on a second side of the boundary, the first and second areas being respectively dimensioned and aligned such that the received energy is not significantly affected by a more than nominal change in at least one of the first and second positions.

59. The method of claim 58, wherein the first and second areas are respectively dimensioned and aligned such that the received energy remains essentially constant notwithstanding the change in at least one of the first and second positions.

60. The method of claim 58, wherein the first and second areas are respectively dimensioned and aligned such that the received energy does not decrease by more than 50% due to the change in at least one of the first and second positions.

61. The method of claim 58, further including an act of providing power to a load based on the received energy.

62. The method of claim 58, wherein:

the first and second areas respectively define parallel planes; and

the first and second areas are respectively dimensioned and aligned such that the first area subtends a third area on the second side of the boundary that completely includes the second area.

63. The method of claim 62, wherein the third area is at least twice as large as the second area.

64. The method of claim 58, wherein:

the act of transmitting the energy from the first area includes an act of transmitting a magnetic field from the first area; and

the act of receiving at least a portion of the energy in the second area as received energy includes an act of receiving at least a portion of the magnetic field in the second area.

65. The method of claim 64, wherein an amplitude of a magnetic flux through the second area remains essentially constant notwithstanding the change in at least one of the first and second positions.

66. The method of claim 64, wherein the act of transmitting a magnetic field from the first area includes an act of transmitting a time varying magnetic field having a frequency in a range of from approximately 200 kHz to 500 kHz.

67. A transcutaneous power transformer, comprising:

a primary winding located external to a body to generate a first magnetic flux; and

a secondary winding located internal to the body and positioned relative to the primary winding so as to receive at least a portion of the first magnetic flux as a second magnetic flux,

wherein the primary winding and the secondary winding are constructed and arranged such that the secondary winding is capable of providing a load with a sufficient power based upon the second magnetic flux irrespective of a significant spatial displacement of at least one of the primary winding and the secondary winding.

68. The transcutaneous power transformer of claim 67, wherein the spatial displacement is an axial displacement.

69. The transcutaneous power transformer of claim 67, wherein the spatial displacement is a lateral displacement.

70. The transcutaneous power transformer of claim 67, wherein the spatial displacement includes at least one of:

an axial displacement of greater than approximately .15 inches; and

a lateral displacement of greater than approximately .25 inches; and

a variation in the sufficient power is less than approximately 50 % due to the spatial displacement.

71. The transcutaneous power transformer of claim 67. wherein the spatial displacement includes at least one of:

an axial displacement of greater than approximately .5 inches; and

a lateral displacement of greater than approximately .25 inches; and

a variation in the sufficient power is less than approximately 50 % due to the spatial displacement.

72. The transcutaneous power transformer of claim 67, wherein:

the primary winding delimits a first area;

the secondary winding delimits a second area; and

the first area is at least twice as large as the second area.

73. The transcutaneous power transformer of claim 72, wherein a ratio of the first area to the second area is in a range of from approximately 2:1 to 80:1.

74. The transcutaneous power transformer of claim 72, wherein the primary winding includes from 3 to 5 winding turns.

75. The transcutaneous power transformer of claim 74, wherein the secondary winding includes from 12 to 16 winding turns.

76. The transcutaneous power transformer of claim 72, wherein the first area is in a range of from approximately 7 to 30 square inches.

77. The transcutaneous power transformer of claim 76, wherein the second area is in a range of from approximately 2 to 7 square inches.

78. The transcutaneous power transformer of claim 72, wherein:

the primary winding includes from 3 to 5 winding turns;

the secondary winding includes from 12 to 16 winding turns;

the first areas is in a range of from approximately 7 to 30 square inches; and

the second area is in a range of from approximately 2 to 7 square inches.

79. The transcutaneous power transformer of claim 72, wherein the primary winding has an approximately circular shape and has a diameter in a range of from approximately 4 inches to 5.5 inches.

80. The transcutaneous power transformer of claim 79, wherein the secondary winding has an approximately circular shape and has a diameter in a range of from approximately 2 inches to 2.75 inches.

81. The transcutaneous power transformer of claim 67, wherein the secondary winding is constructed and arranged so as to be capable of providing the sufficient power in a range of from approximately 15 to 50 watts.

82. The transcutaneous power transformer of claim 81, wherein the secondary winding is constructed and arranged so as to be capable of providing an output voltage in a range of from approximately 15 to 30 volts.

83. The transcutaneous power transformer of claim 82, wherein the primary winding and the secondary winding are constructed and arranged such that the output voltage has a frequency in a range of from approximately 200 kHz to 500 kHz.

84. The transcutaneous power transformer of claim 82, wherein the secondary winding is constructed and arranged so as to be capable of providing an output current in a range of from approximately 2 to 3 amperes.

85. A transcutaneous energy transfer apparatus, comprising:

a primary coil located external to a body to transmit a magnetic field; and

a secondary coil located internal to the body to receive at least a portion of the magnetic field,

wherein the primary coil and the secondary coil are constructed and arranged such that a magnetic coupling between the primary coil and the secondary coil is significantly insensitive to a more than nominal spatial displacement of at least one of the primary coil and the secondary coil.

86. A primary winding for use in a transcutaneous energy device, the transcutaneous energy device comprising the primary winding and a secondary winding, the primary winding comprising:

at least one winding turn to transmit energy based on an electrical signal applied to the at least one winding turn, the primary winding delimiting a first area through which the energy is transmitted, the first area being at least twice as large as a second area delimited by the secondary winding.

87. The primary winding of claim 86, wherein the first area is at least four times as large as the second area.

88. The primary winding of claim 86, wherein the first area is at least nine times as large as the second area.

89. The primary winding of claim 86, wherein the first area is at least sixteen times as large as the second area.

90. The primary winding of claim 86, wherein the first area is at least thirty-six times as large as the second area.

91. The primary winding of claim 86, wherein a ratio of the first area to the second area is in a range of from approximately 2:1 to 80:1.

92. The primary winding of claim 86, wherein the at least one winding turn includes from 3 to 5 winding turns.

93. The primary winding of claim 86, wherein the first area is in a range of from approximately 7 to 30 square inches.

94. The primary winding of claim 86, wherein:
the first area has an approximately circular shape; and
the first area has a diameter of greater than 3.5 inches.

95. The primary winding of claim 86, wherein:
the first area has an approximately circular shape; and
the first area has a diameter in a range of from approximately 3 inches to 6 inches.

96. The primary winding of claim 95, wherein the first area has a diameter in a range of from approximately 4 inches to 5.5 inches.

97. The primary winding of claim 86, wherein:
the first area has an approximately circular shape; and
a ratio of a diameter of the first area to a diameter of the second area is in a range of from approximately 1.5:1 to 9:1.

98. The primary winding of claim 86, in combination with the secondary winding.

99. A primary winding for use in a transcutaneous energy device, the transcutaneous energy device comprising the primary winding and a secondary winding, the primary winding comprising:
at least one winding turn to transmit energy based on an electrical signal applied to the at least one winding turn, the primary winding delimiting a first area through which the energy is transmitted, the first area being at least approximately 9.7 square inches.

100. The primary winding of claim 99, wherein:
the first area has an approximately circular shape; and
the first area has a diameter of greater than 3.5 inches.

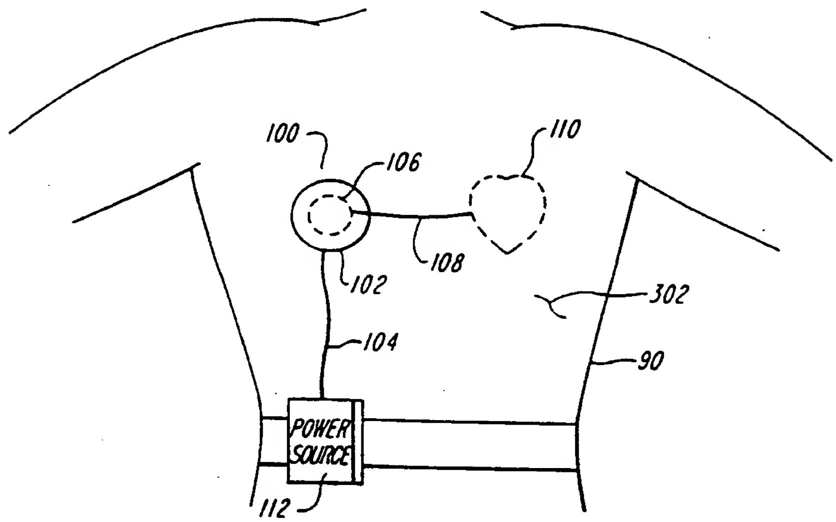

100
106
110
108
102
302
104
90
POWER SOURCE
112

FIG. 1

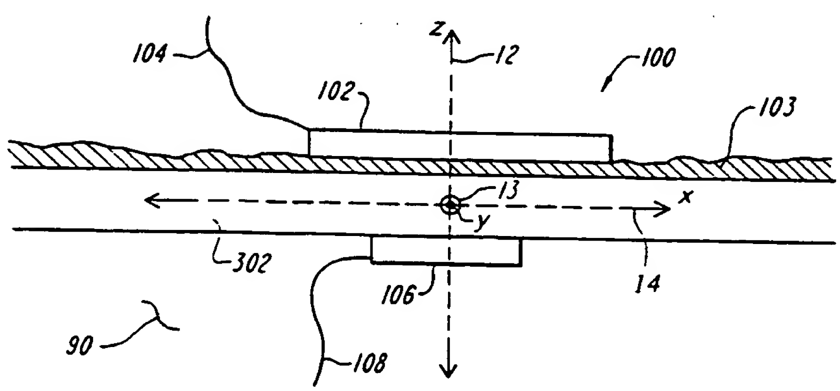

z
12
100
104
102
103
13
x
y
302
14
106
90
108

FIG. 2

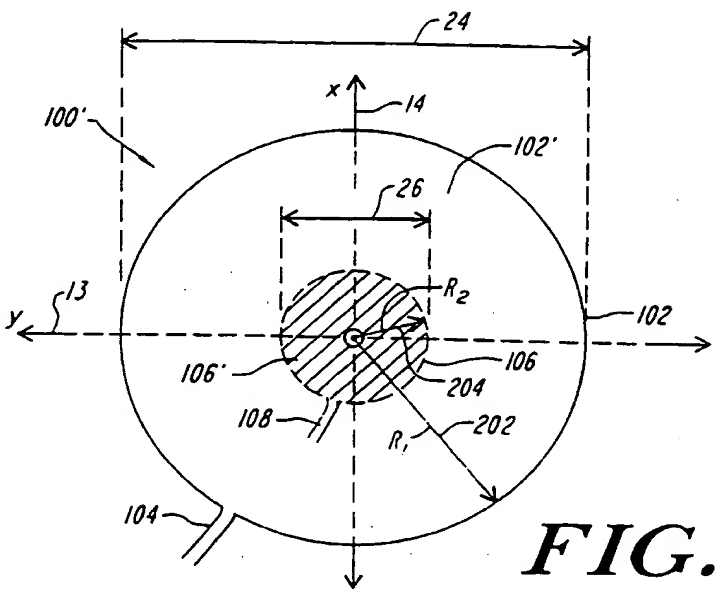

24
x
14
100'
102'
26
R2
13
y
102
106'
106
204
108
202
R1
104

FIG. 3

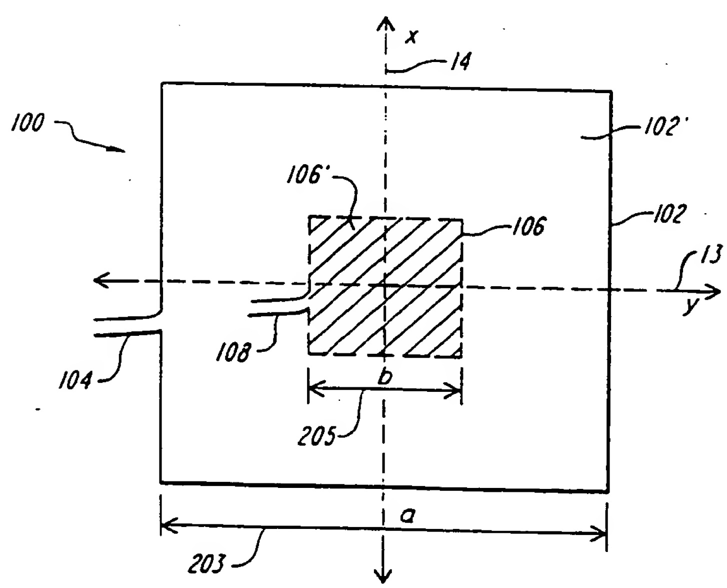

x
14
100
102'
106'
106
102
13
y
108
104
b
205
a
203

FIG. 4

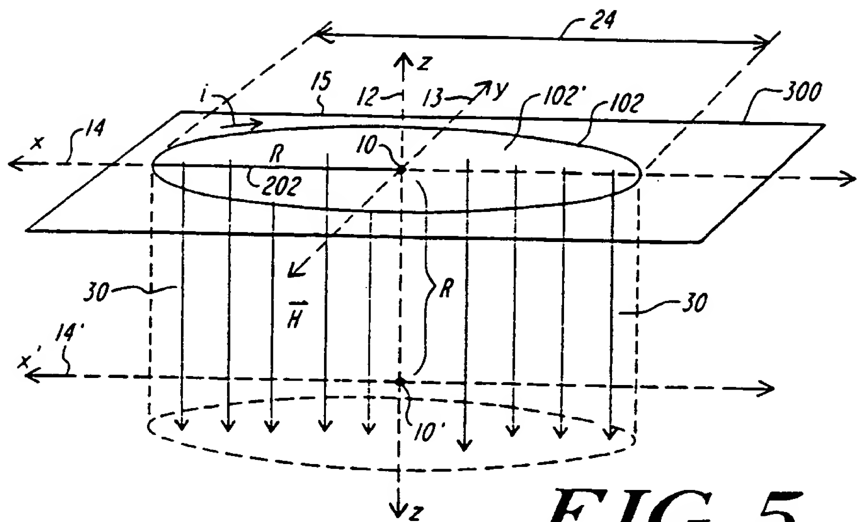

24
z
15
12
13
y
102'
102
300
i
x
14
R
10
202
30
R
H
30
x'
14'
10'
z

FIG. 5

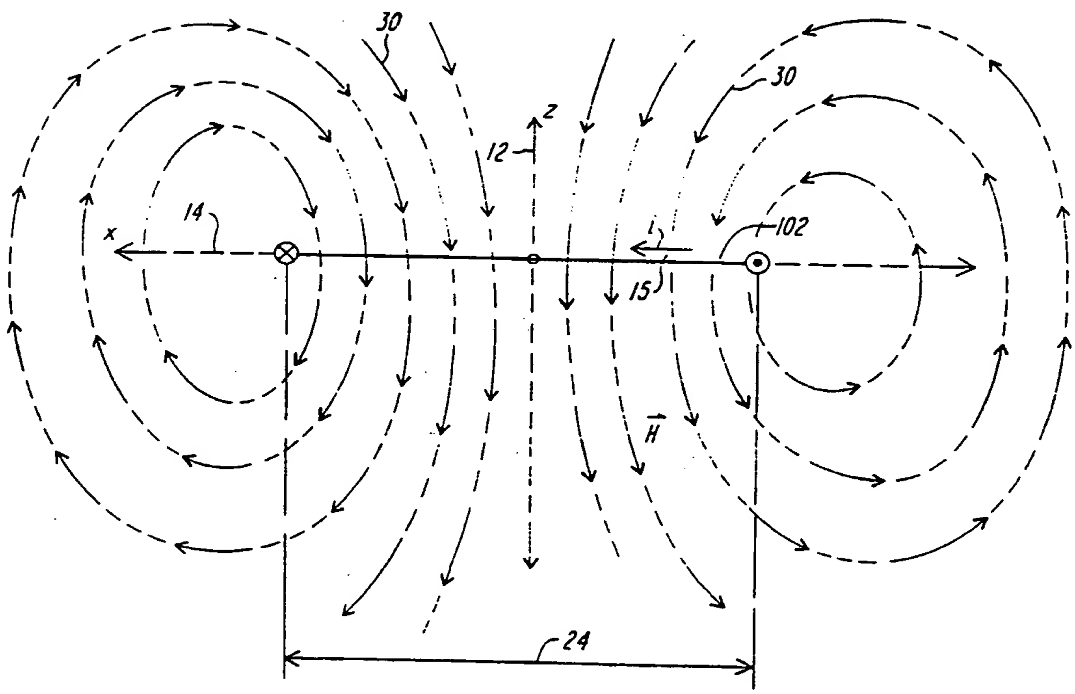
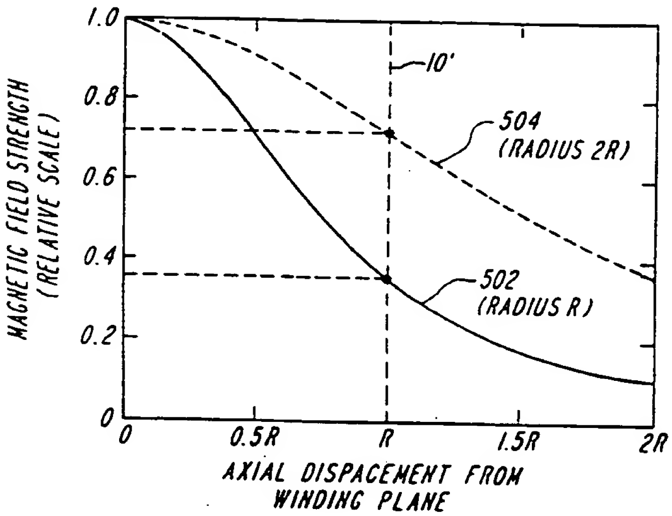
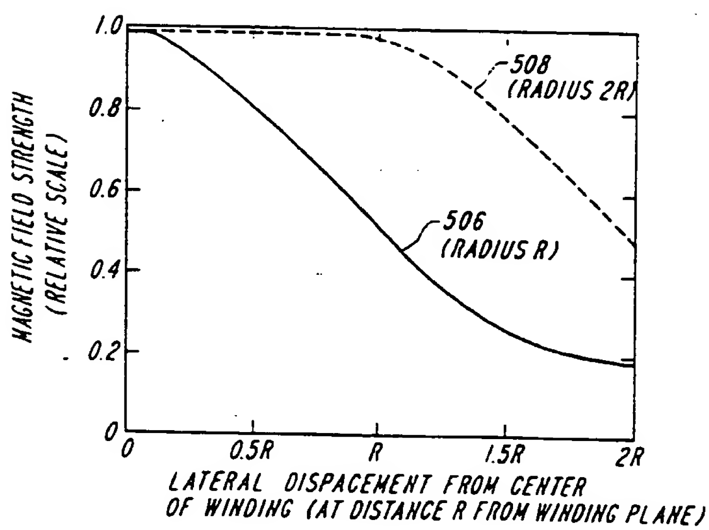

30
30
z
12
14
x
i
102
15
H
24

FIG. 6



1.0
0.8
0.6
0.4
0.2
0
MAGNETIC FIELD STRENGTH (RELATIVE SCALE)
10'
504 (RADIUS 2R)
502 (RADIUS R)
0
0.5R
R
1.5R
2R
AXIAL DISPACEMENT FROM WINDING PLANE

FIG. 7



1.0
0.8
0.6
0.4
0.2
0
MAGNETIC FIELD STRENGTH (RELATIVE SCALE)
508 (RADIUS 2R)
506 (RADIUS R)
0
0.5R
R
1.5R
2R
LATERAL DISPACEMENT FROM CENTER OF WINDING (AT DISTANCE R FROM WINDING PLANE)

FIG. 8

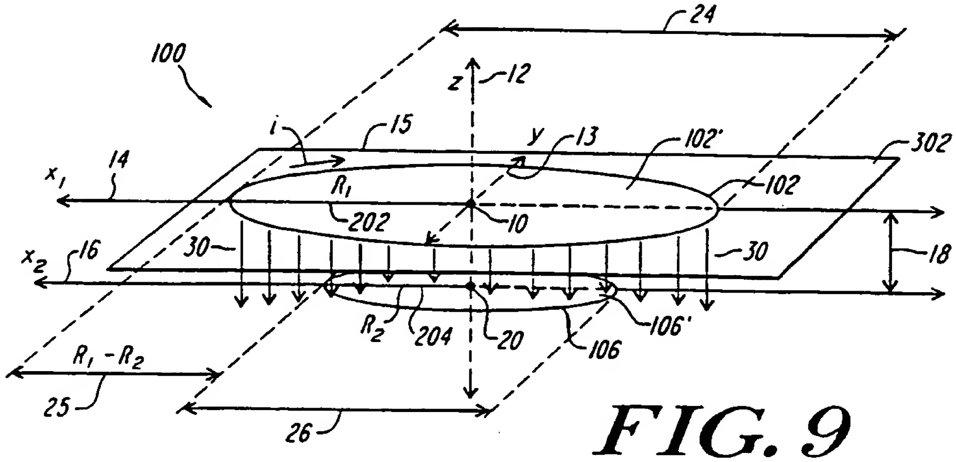


FIG. 9

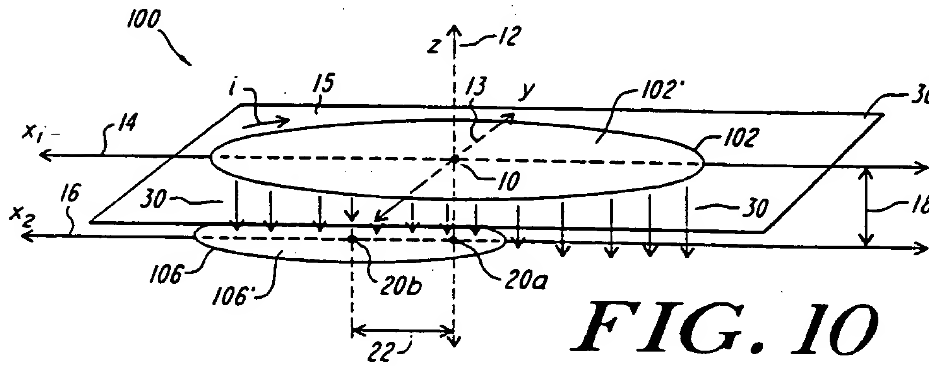


FIG. 10

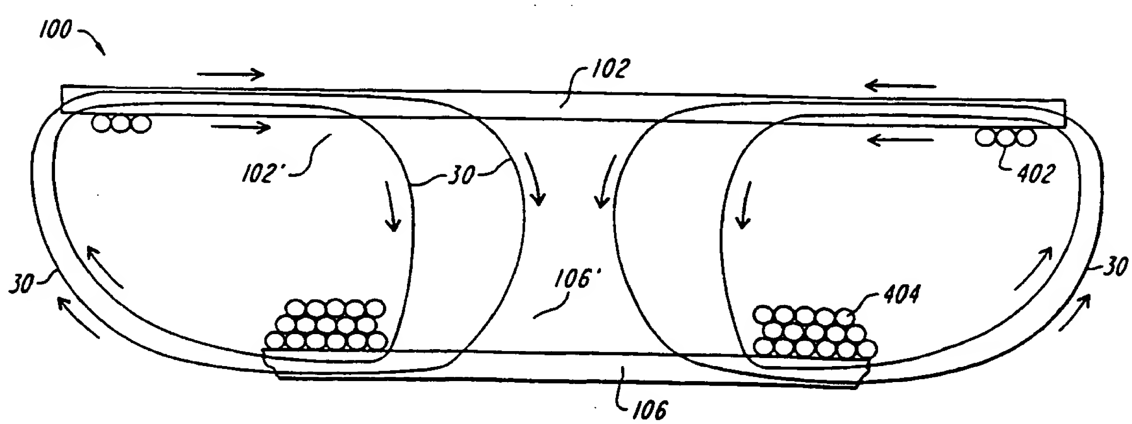


FIG. 11

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 00/31923

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 A61N1/08 A61N1/378

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 A61N H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	DE 37 36 170 A (MESA SYSTEMTECHNIK GES FUER ME) 18 May 1989 (1989-05-18) the whole document ---	1-10, 28-33 14-22, 34-57

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 February 2001	22/02/2001

Name and mailing address of the ISA
European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer
Rakotondrajaona, C

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FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box I.2

Claims Nos.: 28, 67, 85 and claims dependent thereupon (all in part)

Present apparatus claims 28, 67 and 85 and claims dependent thereupon relate to an apparatus in which an attempt is made to define technical features of the apparatus by reference to a desirable characteristic or property, namely the fact that the apparatus is so constructed and arranged that energy transfer between them is not significantly affected by a more than nominal movement or change in the relative positions of the two energy transfer elements making up the apparatus.

The claims cover all apparatus having this characteristic or property, whereas the application provides support within the meaning of Article 6 PCT and/or disclosure within the meaning of Article 5 PCT for only a very limited number of such apparatus. Support and disclosure are present only insofar as the relative dimensions and spacing or positioning of the energy transfer means are specially selected so as to give the desired result. An optimum arrangement is given in Fig 9 of the application. It would appear that the relative sizes and spacing or position of the coils (and specifically, the requirement that one coil be substantially larger than the other) are of critical importance for a proper operation of the alleged invention. It certainly would not be apparent to the skilled reader how one should operate the alleged invention in any other way than that specifically set out in the description. In the present case, the claims so lack support, and the application so lacks disclosure, that a meaningful search over the whole of the claimed scope would be impossible.

Independent of the above reasoning, the claims also lack clarity (Article 6 PCT). An attempt is made to define the apparatus by reference to a result to be achieved. Again, this lack of clarity in the present case is such as to render a meaningful search over the whole of the claimed scope impossible.

Similar comments apply, mutatis mutandis, to method claims 58-66.

Additionally, whilst the claims refer in general terms to energy transfer means, the application provides support only for the use of transformers.

Consequently, the search has been carried out for those parts of the above claims which appear to be clear, supported and disclosed, namely those parts relating to

- a transformer apparatus comprising two separate coils, wherein the spacing or positioning and relative dimensions of the coils are such as to allow small movements between the coils without appreciably affecting the energy transfer between the coils.

-a transformer apparatus as set out above in which the primary coil is larger than the secondary coil

- a method for using this kind of apparatus

INTERNATIONAL SEARCH REPORT

Inte nal Application No
PCT/US 00/31923

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 741 316 A (WILKERSON BRIAN D ET AL) 21 April 1998 (1998-04-21)	1,7-9, 11-15, 28, 32-36, 43,45, 67,68, 72,85, 86,98,99
A	column 3, line 65 -column 6, line 30; figures	2-5, 18-21, 23-27, 29-31, 33, 37-42, 44, 46-53, 69-71, 73-84, 87-96
X	US 5 405 367 A (SCHULMAN JOSEPH H ET AL) 11 April 1995 (1995-04-11)	1-5, 7-15, 28-33, 67-69, 72,73, 85-91, 98,99
A	column 3, line 56 -column 5, line 13; figures	18-21, 25, 36-47, 49-53, 70,71, 74-78, 81,82
X	US 5 703 461 A (MINOSHIMA ET AL) 30 December 1997 (1997-12-30)	1,8,9, 28,34, 35,43
A	column 3, line 53 -column 7, line 23; claim 1; figures	14-18

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